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A tree-ring based reconstruction of Logan River streamflow, northern Utah

Eric B. Allen,[1] Tammy M. Rittenour,[1] R. Justin DeRose,[2] Matthew F. Bekker,[3] Roger Kjelgren,[4] and Brendan M. Buckley[5]

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[1] We created six new tree-ring chronologies in northern Utah, which were used with preexisting chronologies from Utah and western Wyoming to reconstruct mean annual flow for the Logan River, the largest tributary of the regionally important Bear River. Two reconstruction models were developed, a "Local" model that incorporated two Rocky Mountain juniper chronologies located within the basin, and a "Regional" model that also included limber pine and pinyon pine chronologies from a larger area. The Local model explained 48.2% of the variability in the instrumental record and the juniper chronologies better captured streamflow variability than Douglas-fir collected within the Logan basin. Incorporating chronologies from the northern and southern margins of the transition zone of the western precipitation dipole increased the skill of the Regional model ($r^2 = 0.581$). We suggest the increased Regional model skill indicates that both nodes of the western precipitation dipole influence northern Utah climate. The importance of Rocky Mountain juniper in both reconstructions of streamflow for this region suggests that future work should target these trees where more traditionally desirable species are not present. The reconstructions provide the first extended record of streamflow in northern Utah. Preinstrumental streamflows (1605–1921) exhibited considerable variability when compared to the instrumental period (1922–2005). Our findings confirm that the inherent uncertainty in contemporary water management and planning in the region is due to hydroclimatic variability that has persisted for at least the last four centuries.

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1. Introduction

[2] Northern Utah and the greater Salt Lake City metropolitan area along the Wasatch Front Range is one of the most densely populated regions of the semiarid Intermountain West (IMW) and depends primarily upon water stored as winter snowpack. Mountain streams deliver snowmelt to urban areas for irrigation, municipal drinking sources, hydropower, and recreation. Climate models predict the western US will experience reduced snowpack, increased temperatures, and more severe and longer duration droughts [e.g., *Barnett et al.*, 2004; *Cook et al.*, 2004; *Barnett and Pierce*, 2009]. Climate change is predicted to reduce regional water availability and intensify the effects of droughts and their economic impact [*Rauscher et al.*, 2008]. Furthermore, long-term drought forecasts of months to years, available for much of the western US, have less skill for northern Utah because Pacific Ocean teleconnections are complex and not well understood [*Mock*, 1996; *Dettinger et al.*, 1998; *Wise*, 2010a]. Streamflow records are crucial for informing IMW water managers of natural variability, but regionally are limited to relatively short instrumental records. We aim to improve the understanding of streamflow variability for northern Utah by reconstructing one of the region's major streams, the Logan River.

[3] Northern Utah falls in the transition zone of the western precipitation dipole, a generalized observation of western US precipitation patterns that has been shown to be driven by the El Niño Southern Oscillation (ENSO), but is also modulated by the Pacific Decadal Oscillation (PDO) [*Mock*, 1996; *Cayan et al.*, 1999]. During El Niño conditions the American Southwest is wet while the Pacific Northwest is dry, and La Niña conditions produce the opposite pattern [*Redmond and Koch*, 1991; *Dettinger et al.*, 1998]. While the current, mean position of the transition zone between these nodes falls between the latitudes ~40–42°N [*Wise*, 2010a], an area encompassing the Logan River (Figure 1), the dipole likely shifted modestly in the

[1]Department of Geology, Utah State University, Logan, Utah, USA.
[2]Forest Inventory and Analysis, Rocky Mountain Research Station, Ogden, Utah, USA.
[3]Department of Geography, Brigham Young University, Provo, Utah, USA.
[4]Department of Plant, Soils, and Climate, Utah State University, Logan, Utah, USA.
[5]Tree Ring Laboratory, Lamont-Doherty Earth Observatory, Palisades, New York, USA.

Corresponding author: E. B. Allen, Department of Geology, Utah State University, 4505 Old Main Hill, Logan, UT 84322-4505, USA. (ericballen@gmail.com)

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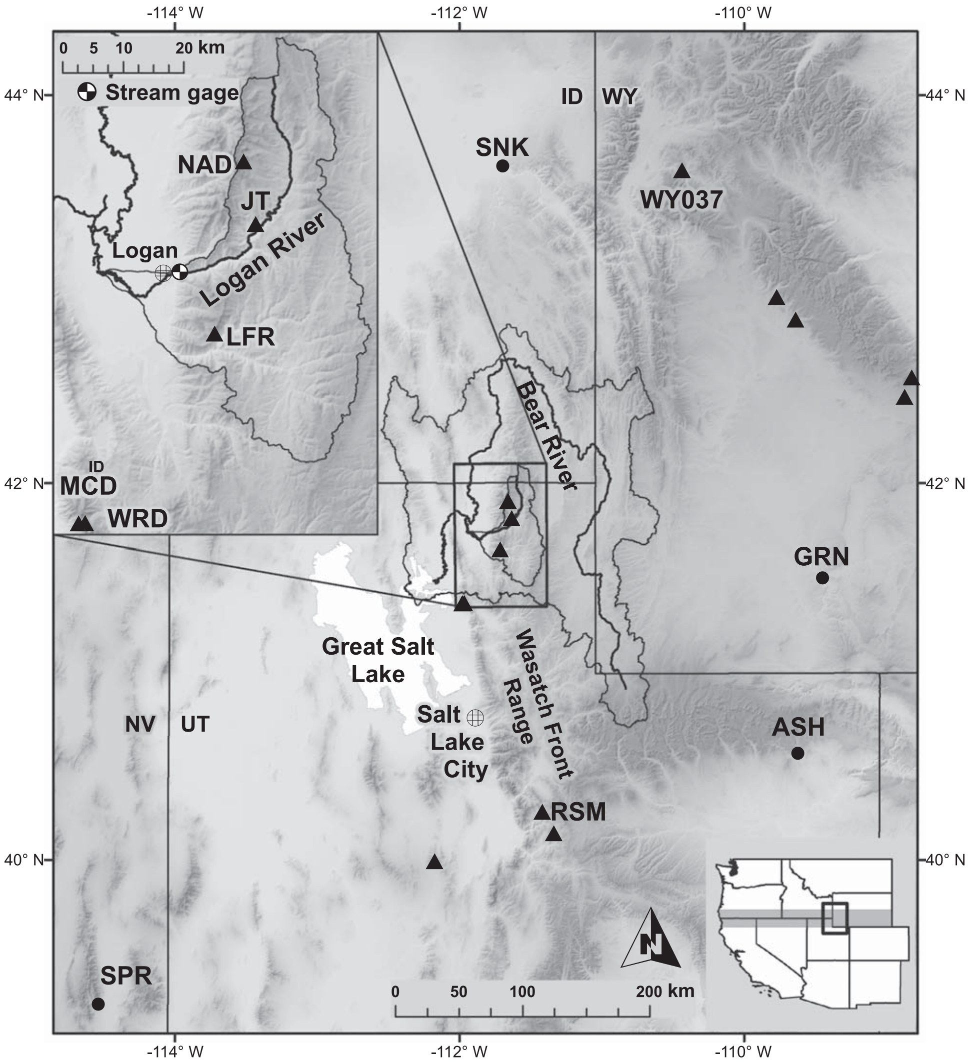

Figure 1. Main map shows the Logan River basin (smaller polygon), Bear River Basin (larger 1 polygon), chronologies (triangles) considered from the region with assumed hydroclimatic coherence, and locations of gages of nearby flow reconstructions (filled circles, ASH = Ashley Creek, GRN = Green River, SNK = Snake River, SPR = Spring Valley). (top left) Inset shows the Logan River basin and associated gage and location of chronologies created by this study. Both JTR and JTD are located at JT. (bottom right) Inset shows the outline of the larger map and the current mean position of the transition zone of the western precipitation dipole (gray) as described by *Wise* [2010a].

past [*DeRose et al*., 2013]. In northern Utah, winter precipitation and ENSO phase do not correlate well as there is an equal chance of either node modulating winter precipitation in a given year. However, quasi-decadal scale changes in Gulf of Alaska circulation associated with phase transitions of the PDO have been shown to modulate IMW precipitation [*Zhang et al*., 1997; *Wang et al*., 2009].

[4] A long-term perspective on northern Utah streamflow beyond the historical record is key to understanding regional hydrologic drought cycles and improving water management strategies. We created a long-term streamflow record by developing tree-ring chronologies, normalized indices of annual tree growth [*Cook*, 1985] (Figure 1) to reconstruct the last several centuries of mean annual flow of the Logan River. Two-needle pinyon pine (*Pinus edulis*) and Douglas-fir (*Pseudotsuga menziesii*) are conventionally the most desirable species for streamflow reconstructions, while ponderosa pine (*P. ponderosa*) and Douglas-fir are most useful for precipitation reconstructions in the western U.S. [*Hidalgo et al*., 2001]. However, the study region falls largely outside the geographical limits of these trees except for Douglas-fir. Hence, we developed chronologies using Douglas-fir and locally available Rocky Mountain juniper (*Juniperus scopulorum*), which is seldom used in dendroclimatic reconstructions.

[5] The Logan River originates in the Bear River Range of northern Utah (Figure 1), and supplies the greater City of Logan area with agricultural and municipal irrigation water, and supports two hydropower dams. The Logan River is the largest tributary (24% of mean flow) to the Bear River, which in turn is the largest tributary to the Great Salt Lake [*Utah Division of Water Resources*, 2000].

Table 1. Descriptive Statistics of Chronologies Created by This Study and Considered for Modeling as Well as Preexisting Chronologies Retained for Modeling[a]

Chronology	Species	Oldest Ring	Elevation (m)	Trees (series)	Mean Sensitivity	Interseries Correlation	Author
JTD	PSME	1511	2100	26 (46)	0.193	0.670	This study
JTR[LR]	JUSC	1227	2100	26 (49)	0.227	0.605	This study
LFR[LR]	JUSC	1174	1980	23 (40)	0.275	0.645	This study
MCD	PSME	1370	2290	54 (103)	0.248	0.660	This study
NAD	PSME	1274	2730	35 (59)	0.177	0.537	This study
WRD	PSME	1133	2740	41 (58)	0.213	0.592	This study
RSM[R]	PIED	1428	2130	28 (52)	0.311	0.688	*Bekker et al.* [2013]
WY037[R]	PIFL	1315	2300	29 (68)	0.265	0.613	*Wise* [2010b]

[a]Note the greater sensitivity of the Rocky Mountain juniper compared to the Douglas-fir chronologies. Chronology locations are shown in Figure 1.
[L]Chronology used in Local model. JUSC = *Juniperus scopulorum*, PIED = *Pinus edulis*, PIFL = *Pinus flexilis*.
[R]Chronology used in Regional model. PSME = *Pseudotsuga menziesii*.

The Bear River is the last major stream not yet fully developed in the region, but is crucial for future water allocations designed to support the region's rapidly growing population [*Mackun and Wilson*, 2011]. The Salt Lake City and Wasatch Front metropolitan populations are projected to double and exceed existing water supplies by 2050 [*Utah Division of Water Resources*, 2000].

[6] Our research supports water management in northern Utah by using dendrochronology, the process of using tree-ring data to reconstruct past events, to extend Logan River mean annual water-year flows (MAF) back to the year 1605. We accomplish this by first developing six new tree-ring chronologies in the area [*Allen*, 2013], including two comprising Rocky Mountain juniper which we evaluate for its feasibility for use in streamflow reconstructions. We use these chronologies to model Logan River MAF with a "Local" model, which employs only within-basin chronologies, as well as a "Regional" model, which also includes chronologies from a larger area defined by similar synoptic climatology [*Woodhouse et al*., 2006; *Barnett et al*., 2010]. The resulting reconstructions provide water managers with a longer-term record of streamflow for use in water planning. The Regional reconstruction is compared to the four closest streamflow reconstructions from the IMW to characterize spatial and temporal coherence in hydroclimate.

2. Study Area

[7] The Logan River drains 1389 km^2 of the Bear River Range in southeastern Idaho and northern Utah, USA (Figure 1). The Bear River Range is located in the IMW at the boundary between the Great Basin to the west and Rocky Mountains to the east. Elevations in the Logan River basin range from 3035 m at Naomi Peak to 1341 m at the confluence with the Bear River west of Logan. Annual precipitation in the region is dominated by winter snowfall delivered by storms that originate in the Pacific Ocean [*Mock*, 1996; *Brown and Comrie*, 2004]. Peak daily discharges of the Logan River are associated with snowmelt from May through July and MAF is strongly correlated ($r^2 = 0.675$) with annual precipitation.

3. Data and Methods

3.1. Flow Data

[8] We acquired naturalized daily streamflow data for the water years 1922–2010 for USGS gage 10109001 (online at http://nwis.waterdata.usgs.gov). The gage is located near the city of Logan, with an upstream drainage area of 554 km^2 (Figure 1). The daily data were compiled into water year means (October–September). Naturalized flow data account for anthropogenic streamflow alterations such as dams and diversions. Although the locations of gages used to calculate naturalized flows have been moved, uncertainty in MAF over the entire record is considered to be $\pm 5\%$ of the values provided by the USGS (online at http://wdr.water.usgs.gov).

3.2. Tree-Ring Data

[9] Due to the limited number of existing tree-ring chronologies in the region, six new chronologies were created from the Bear River Range (Logan River basin) and surrounding mountains (Table 1; Figure 1). Each site was chosen based on growing conditions known to induce water stress, including poor soil development, southward to westward aspect, steep rocky slopes, and generally open canopy conditions [*Fritts*, 1976; *Speer*, 2010]. Douglas-fir and Rocky Mountain juniper were sampled at four and two sites, respectively, in northern Utah (Figure 1). The Douglas-fir site on Naomi Peak (NAD) updated an existing chronology by *Woodhouse and Kay* [1990] [also see *Woodhouse*, 1989]. Where possible, we extracted two cores from each living tree, and collected remnant wood samples to extend the chronology further into the past. The cores were mounted on wooden blocks and sanded with progressively finer sandpaper up to at least 400 grit. The pairs of cores from each tree were visually crossdated prior to being measured to the nearest 0.001 mm [*Stokes and Smiley*, 1968; *Fritts*, 1976; *Speer*, 2010], and the quality of crossdating was statistically assessed using the program COFECHA [*Holmes*, 1983].

[10] We used the program ARSTAN to remove so-called biological growth patterns associated with tree age [*Fritts*, 1976; *Cook et al*., 2007]. We then averaged the resulting indices using a robust mean to create a site chronology [*Fritts*, 1976; *Cook and Kariukstis*, 1990]. We considered various detrending options to best preserve the high-frequency signal and chose the Friedman variable span smoother using an alpha value of 5 [*Friedman*, 1984]. This approximates a moderately flexible smoothing spline which preserves some lower frequency variation.

[11] The sensitivity of the chronologies to climate was assessed using maximum monthly temperature during late spring and early summer, assumed to limit the growing

Table 2. Verification Statistics of the Models Using a Split Sample Calibration Method[a]

	Calibrate 1922–1962					Calibrate 1963–1999					Full Model 1922–1999		
Model	r^2	Adj. r^{2b}	RE	CE	r^2 (PRESS)	r^2	Adj. r^2	RE	CE	r^2 (PRESS)	r^2	Adj. r^2	r^2 (PRESS)
Local	0.287	0.251	0.534	0.505	0.189	0.582	0.560	0.286	0.194	0.511	0.482	0.469	0.439
Regional	0.377	0.309	0.641	0.620	0.220	0.691	0.657	0.338	0.252	0.599	0.581	0.559	0.525
Local	$=3.765 - (8.075 \times \text{JTR}) + (11.346 \times \text{LFR})$												
Regional	$=2.743 - (8.643 \times \text{JTR}) + (8.482 \times \text{LFR}) + (2.920 \times \text{RSM}) + (1.610 \times \text{WY37.lag})$												

[a]The models were calibrated on one half of the streamflow record and verified on the other half before a full reconstruction model was built.
[b]Adj. r^2 = adjusted r^2, RE = Reduction of Error, CE = Coefficient of Efficiency, PRESS = Predicted Residual Sum of Squares.

season, and monthly and water-year precipitation. The values were obtained from the PRISM grid cell associated with each site (PRISM Climate Group online at http://prism.oregonstate.edu). PRISM data were used due to its suggested strength relative to station data [*Blasing and Duvick*, 1981] and the relative shortness of the nearby Tony Grove SNOTEL station (in operation since 1978). The analysis was conducted using a bootstrapped correlation between each chronology as well as its 1 year lag, to account for autocorrelation, and its associated climate data for the entire period of record (1895–2010) [*Biondi and Waikul*, 2004; *Zang*, 2012]. We determined that each chronology had significant ($p \leq 0.05$) relationship to either mean maximum monthly temperature or mean monthly precipitation [*Allen*, 2013]. We verified the temporal stability of the chronologies sensitivity to monthly climate using a 31 year moving window analysis.

[12] In addition to chronologies developed for this study, we also considered previously existing chronologies in a region defined by synoptic climatology [e.g., *Woodhouse et al*., 2006; *Barnett et al*., 2010]. This region includes central to southwestern Wyoming, the Wasatch Front Range in Utah, and southeastern Idaho and experiences a similar hydroclimate as the Logan River basin [*Wise*, 2010a]. Three limber pine (*Pinus flexilis*), two Douglas-fir, one single-needle pinyon pine (*Pinus monophylla*), and two two-needle pinyon pine chronologies were acquired online from the International Tree-Ring Data Bank (http://www.ncdc.noaa.gov) and considered for modeling along with chronologies created by this study [*Contributors of the International Tree-Ring Data Bank*, 2013]. All chronologies considered encompass a common period of 1584–2000. These 14 climatically sensitive chronologies were expanded to a predictor pool of 28 by including significantly correlated 1 year lags in order to account for autocorrelation found in tree-growth and climate [*Fritts*, 1976; *Cook and Kairiukstis*, 1990; *Meko and Graybill*, 1995]. Autocorrelation in tree-growth represents carryover of resources from 1 year to the next. Thus, growth in the year following favorable conditions will be advantaged relative to a year following poor growing conditions [*Fritts*, 1976].

3.3. Model Building

[13] Previous researchers examined the relative strength of chronologies from within a stream basin compared to a suite of chronologies from a larger area [e.g., *Woodhouse et al*., 2006; *Barnett et al*., 2010]. Here we used two groups of predictors to build two models of Logan River water year MAF (in cms, cubic meters per second). The Local model included predictors within 100 km of the Logan River basin boundary following *Watson et al*. [2009], and the Regional model incorporated all predictors within an area of putatively similar hydroclimate (Figure 1). The two models were compared to assess the ability of within-basin chronologies to model Logan River MAF. Each group of predictors was entered into a stepwise linear regression model ordered by their correlation to Logan River MAF. Predictors were retained based on AIC (Table 2). The models were verified using a split calibration procedure in which the period of overlap between the streamflow record and tree-ring data was divided in half, and the model was calibrated on the first half and its skill verified on the second half. The model was then calibrated on the latter half of the flow record and verified on the first half. The model skill of split and full calibration were assessed using r^2, adjusted r^2, reduction of error (RE), coefficient of efficiency (CE), and the PRESS statistic (Table 2) [*Fritts*, 1976; *Cook and Kariukstis*, 1990]. The reduction of error, RE, is a measure of model skill that compares the variance of predicted from observed values versus the variance of observed values from the calibration period mean. CE differs from RE in that it uses the validation period mean instead of the calibration period mean. RE and CE values range from 1 to negative infinity, and although there is not a significance threshold, a value greater than zero indicates some degree of model skill. Using the validation-period mean results in CE being smaller, and more stringent, than RE. Due to the higher RE and CE values of the Regional model, it will be used when discussing reconstructed MAF unless otherwise noted.

4. Results

4.1. Model Results

[14] Reconstructed Logan River water year MAF for both the Local and Regional models extended back to 1605, augmenting the instrumental record by over 300 years. Prior to this year, the subsample signal strength of LFR dropped below 0.85, a suggested minimum threshold of a chronology's signal strength [*Wigley et al*., 1984]. The two within-basin Rocky Mountain juniper chronologies were retained in both models, while the Regional model also incorporated a two-needle pinyon chronology from north-central Utah and a limber pine chronology [*Wise*, 2010b] from western Wyoming (Figure 1). The additional chronologies resulted in greater Regional model skill ($r^2 = 0.581$) compared to the Local model ($r^2 = 0.482$, Table 2, Figure 2). This level of model skill was similar to other stream reconstructions, such as 0.52 on the Yellowstone River [*Graumlich et al*., 2003], 0.713 on Ashley Creek [*Carson and Munroe*, 2005], 0.475 in the Green

Table 3. Overlapping 5 Year Extreme Low Flow Periods (≤95% Exceedance) of Select Reconstructions With at Least 3 Years of Overlap With Low Flow Periods of the Logan River Regional Model (1605 to Present)[a]

Year	Logan River	Snake River [*Wise*, 2010b]	Green River [*Woodhouse et al*., 2006]	Ashley Creek [*Carson and Munroe*, 2005]	Spring Valley [*Strachan et al*., 2012]
1628		−0.774			
1629	−0.972	−0.943			
1630	−1.186	−1.324			−0.965
1631	−1.162	−0.964			−0.814
1632	−1.162				
1633		−0.779			
1651	−1.106				
1652					−1.213
1653					−1.551
1733				1.148[b]	
1735	−1.044				
1736	−1.152				
1737	−1.170				
1757			−0.809		
1758	−1.017				
1759	−0.969				
1844			−0.882		−0.883
1845			−0.801		
1846	−1.059		−1.313		
1847	−1.042		−0.869		
1887	−0.975	−0.821			
1888	−1.301		−0.681		
1889	−1.151				
1890	−1.048				
1932	−1.127	−1.186			
1933	−1.099	−0.969			−0.845
1934			−0.659		
1989		−0.866			
1990	−1.305	−1.055			
1991	−1.137				
2001		−1.064			
2002	−1.081	−1.267			
2003		−1.172			

[a]Values are the 5 year mean z-score centered on the year indicated.
[b]High-flow period.

River [*Woodhouse et al*., 2006], 0.40–0.64 on the Wind River headwaters [*Watson et al*., 2009], and 0.56–0.63 on the Snake River [*Wise*, 2010b]. Both models exhibited greater skill when calibrated on the latter half of the instrumental record (Table 2). Averaged MAF for the calibration period for each model (6.94 cms) was slightly greater than the observed average (6.92 cms). Both models exhibited less variability during the calibration period, as inferred from the standard deviation, than the observed record. The Local model exhibited slightly less variability (1.48 cms) than the Regional model (1.62 cms).

4.2. Reconstructed Droughts

[15] The Regional reconstruction exhibited multiple extreme (5th percentile) individual dry years both within the instrumental period (1961 and 1934) and prior to measurements (1889, 1864, 1845, 1795, 1777, 1760, 1735, 1729, 1653, 1632). Of the most extreme individual dry years of the entire reconstruction (1934, 1889, and 1735), one was experienced during the instrumental period (Figure 3). Both the Local and Regional models indicated that 1735 was the lowest individual flow year for the entire reconstruction period. Lower-frequency variability (5 year moving average, Figure 3, Table 3) indicated that extended periods of below average flow characterized the Logan River (e.g., 1630s, 1650s, 1755–1965, late 1840s, late 1880s, early 1930s, and late 1980s). Limited coherence occurred between the Logan reconstruction and other nearby streamflow reconstructions. For example, the Logan River and the Snake River shared multiple low flow years in the early 17th century, and again in the 20th. The Logan River and Spring Valley only share three low flow years in common: 1630, 1631, and 1933. In contrast, the Logan River and Ashley Creek shared virtually no low flow events. Coherence between the Logan River and the Green River occurred almost entirely in the 19th century (Table 3).

4.3. Reconstructed Pluvials

[16] Individual high flow years were reconstructed in 1986, 1984, 1983, 1907, 1811, 1793, and 1726–1727 (Figure 3). All high flow years occurred in extended periods of above-average flow, putative pluvials. Lower-frequency variability indicated by the 5 year running average revealed the early 1980s was the most extreme pluvial in the record, followed by the early 1900s. Historical pluvials approaching the 20th century magnitude include the 1790s, 1720s, and 1640s (Figure 3).

5. Discussion

5.1. Model Analysis

[17] Two-needle pinyon pine and ponderosa pine, desirable species in dendroclimatology, are not sufficiently old or

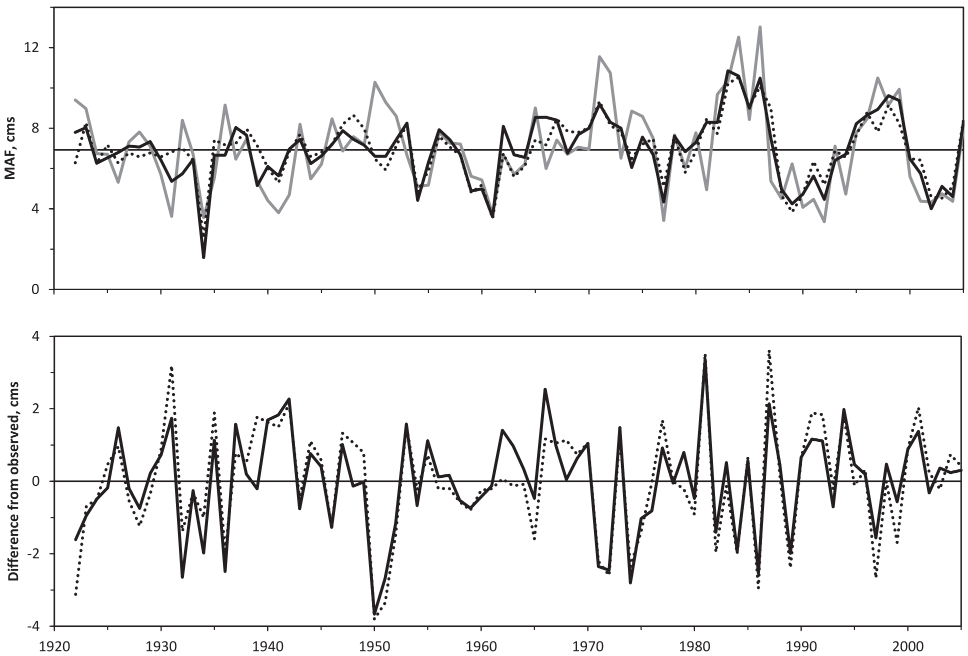

Figure 2. Plot of model calibration with top plot displaying observed mean annual flow (solid gray line), Regional model (solid black line, $r^2 = 0.581$), and Local model (dotted black line, $r^2 = 0.482$). Bottom plot is departure of modeled flows (Regional model solid black line, Local model dotted line) from the instrumental mean (indicated by gray line).

abundant in the Logan River basin or surrounding mountains. Commonly used Douglas-fir is present in the region and were sampled, but exhibit low (0.10–0.19) to intermediate (0.20–0.29) sensitivity [as defined by *Holmes*, 1983] (Table 1). Rocky Mountain juniper, rarely used in dendroclimatology studies, is relatively abundant in the region, and exhibits a higher sensitivity than Douglas-fir and limber pine (Table 1). We successfully use two within-basin juniper chronologies to model Logan River MAF ($r^2 = 0.482$), indicating that this species is sensitive to the local climate and captures a substantial portion of the regional hydroclimatic variability. Although Rocky Mountain juniper has been proposed for use in dendroclimatology [e.g., *Sieg et al*., 1996], there are few examples [but see *Graumlich et al*., 2000] and only three such chronologies are available from the International Tree Ring Data bank. This juniper species is common in the region and across a wide ecological range encompassing much of the western US and parts of Canada (Natural Resources Conservation Service, online http://plants.usda.gov). Juniper abundance, climatic sensitivity [*Sieg et al*., 1996], and propensity for longevity (Table 1) suggest it could be an important species for climate reconstructions, especially where traditionally used species are not present or not sufficiently sensitive as measure by interannual growth [*Holmes*, 1983].

[18] It is noteworthy that the within-basin Rocky Mountain juniper chronologies developed for this project are the only significant predictors retained for use in the Local model. When additional chronologies located in an area with putatively similar climate teleconnections and hydroclimate are considered, the Rocky Mountain junipers are retained as significant predictors. Chronologies of varying species and elevations within 100 km of the Logan River basin are not significant predictors, and therefore excluded from the final models (Table 1; Figure 1). This suggests that inclusion of limber pine (WY037) and two-needle pinyon pine (RSM) in the Regional model may not be entirely due to their species or elevation (Table 1). Instead, we interpret this result as the ability of the distant chronologies to capture the variability in precipitation from the more northern and southern modes at the margins of the transition zone of the western precipitation dipole. In other words, the inclusion of the limber pine chronology (WY037) to the north and single-needle pinyon pine chronology (RSM) to the south likely better capture the regional hydroclimatic variability (Figure 1, Table 1).

[19] Both models generally capture low and moderate flow events, but commonly underestimate extreme high flow events. Predicting extremes, which we define as below the 95% percentile and above the 5% percentile, is difficult as the relationship between precipitation and ring-width response becomes nonlinear, yet the models assume a linear relationship [*Fritts*, 1976; *Briffa*, 1995]. The split calibration reveals that both models exhibit greater skill when calibrated on the more variable latter half of the instrumental record which contains the highest observed flow events (Figure 2). Conversely, calibrating models on the first half and predicting the latter half requires predicting flows well beyond the calibration values, resulting in decreased model skill. Analysis of the relationship between MAF and PRISM water year precipitation suggests that the first half of the streamflow record may be of lower quality than the latter half [*Allen*, 2013]. MAF and precipitation are moderately correlated (<0.50) for the period prior to 1966, after which their correlation increases. A similar, but less

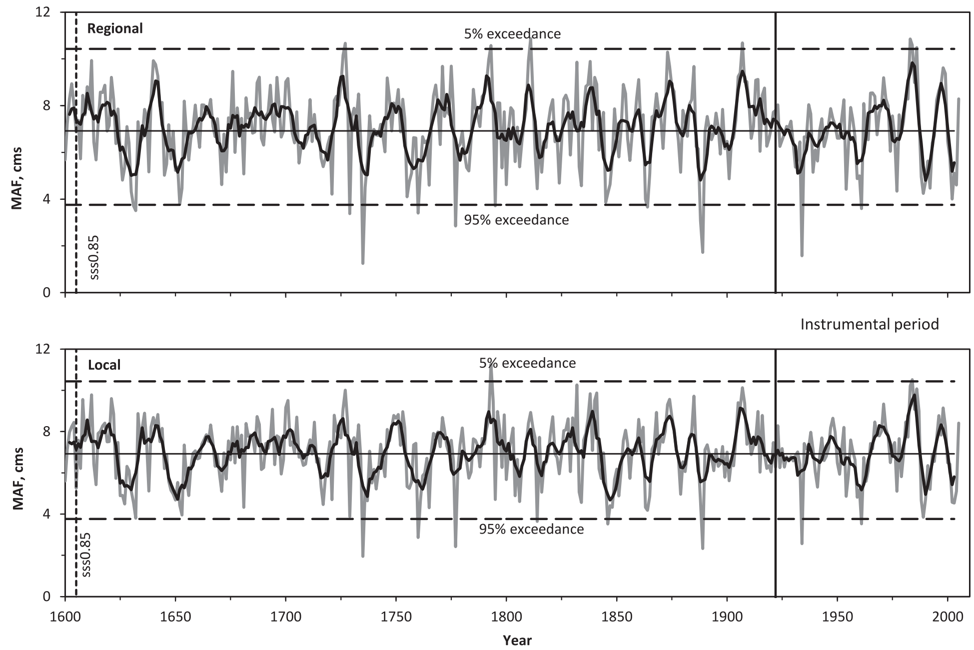

Figure 3. Annual and 5 year mean reconstructed flows of the Logan River of the Regional (top) and Local (bottom) models. The vertical dashed line indicates the sss = 0.85 cutoff [*Wigley et al.*, 1984], the solid vertical line indicates the 1922 instrumental period, and the solid gray horizontal line indicates the instrumental mean. Instrumental exceedance values and mean calculated using individual years of the instrumental period.

pronounced, decline in correlation between tree-ring data and MAF is observed.

5.2. Regional Hydroclimatology

[20] Previous analyses of ENSO teleconnections with winter precipitation suggest that northern Utah and the Logan River drainage are located in the transition zone of the western precipitation dipole [*Wise*, 2010a]. Northwestern Wyoming, where WY037 is located, is more commonly correlated with precipitation patterns in the Pacific Northwest node [*Wise*, 2010a]. The location of WY037 and its significant contribution to Logan River MAF reconstructions suggests that it may contribute a precipitation signal that is most often correlated with the northern mode of the precipitation dipole. Conversely, RSM is located in the southern Wasatch Mountains, an area that *Wise* [2010a] suggested is more commonly correlated with the southern mode of the western precipitation dipole. By considering chronologies from locations north and south of the Logan Basin we more effectively captured this complex climate interrelationship over the last ~400 years. Previous work has shown that only considering within-basin chronologies can be restrictive due to the limited area from which to locate sites [e.g., *Woodhouse et al.*, 2006; *Watson et al.*, 2009; *Barnett et al.*, 2010]. Inclusion of RSM and WY037 suggest that in addition to spatial limitations, introducing chronologies from a broader region in an area with complex terrain based on synoptic climatology is necessary to better model past climate. Moreover, *Watson et al.* [2009] found that considering chronologies across a larger region may be necessary for small headwater streams, as the limited basin size only permits a small area from which to locate sufficiently sensitive chronologies. We similarly note that including chronologies from outside the Logan River Basin improved model skill by 0.099%, indicating that the within basin junipers capture a significant portion, but not all, of the local hydroclimate.

[21] Other stream reconstructions from the central Rocky Mountains and IMW allow for a comparison of regional hydroclimate patterns with respect to the western precipitation dipole. Reconstructions of the Snake River at Heise, ID (210 km north), Green River at Green River, WY (200 km east), Ashley Creek, UT (230 km east), and Spring Valley, NV (360 km southwest) were selected (Figure 1). The Snake River is in the northern node of the western precipitation dipole, Spring Valley in the southern node, and Ashley Creek and the Green River in the transition zone as described by *Wise* [2010a]. Z-scores of annual reconstruction values were smoothed using a 5 year moving average in order to compare coherence of wet and dry periods. These streams and the Logan River exhibit similar interannual flow patterns which differ in magnitude between basins, such as the high-flow year 1839 which is greater in the Green River compared to the Snake or Logan Rivers.

[22] At times, the reconstructed flows are divergent north to south and at other times they are coherent (Figure 4). The 1880s drought in the northerly Logan and Snake River catchments is contemporaneous with greater than average flows of Spring Valley, exemplifying the north-south nature of the western precipitation dipole. Periods such as the 1650s low flows in the Logan River and Spring Valley suggest times when the Logan River hydroclimate is more representative of the southern node of the western precipitation dipole. These periods last from a few years up

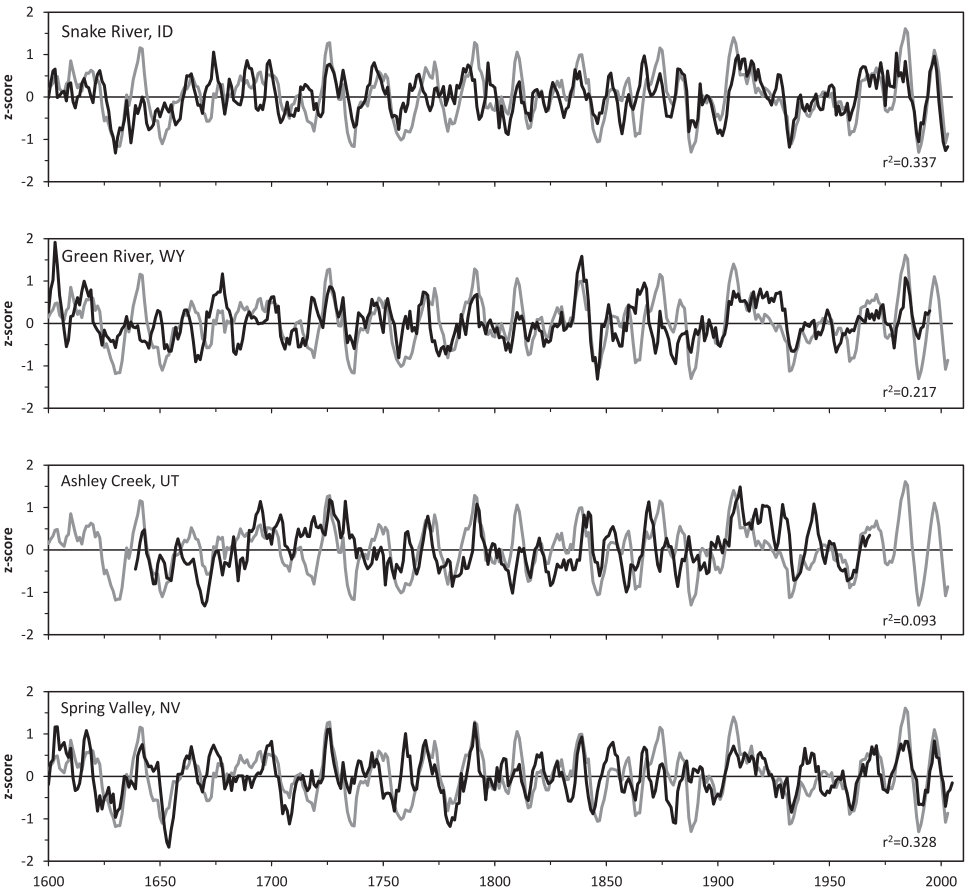

Figure 4. Five year, centered, running-averages of select regional streamflow reconstructions. Logan River Regional model (gray) with, from top to bottom (spatially north to south) in black lines, the Snake River near Heise, ID [*Wise*, 2010b], Green River near Green River, WY [*Woodhouse et al*., 2006], Ashley Creek, UT [*Carson and Munroe*, 2005], and Spring Valley, NV [*Strachan et al*., 2012]. Coefficients of determination were calculated between the stream indicated and the Logan River.

to a decade, a similar length of time as ENSO, suggesting the importance of teleconnections on Logan River hydroclimate.

[23] Coherence with the Logan River occurred in both wet and dry periods (e.g., early 1900s and 1720s wet periods and the dry 1930s). This indicates periods of hydroclimatic coherence similar to other findings [*Fye et al*., 2003]. While the 1730s is dry in the Logan, Green, and Snake reconstructions, Ashley Creek, however, exhibits higher than average flows (Table 3, Figure 4). This dry period has been similarly observed in widely spaced reconstructions across the western US [*Meko and Woodhouse*, 2005]. Ashley Creek exhibits several instances of differing flow patterns from the other streams throughout the reconstructed period. This difference is also demonstrated by the lower coefficient of determination between Ashley Creek and the Logan River compared to the other streams. The Snake River and Spring Valley are significantly more correlated with the Logan River, despite the close proximity of the Green River and Ashley Creek. These differences are likely due to the much large catchments represented by the Green River reconstruction (also the Snake River) that allows them to capture a broader spatial hydroclimate signal, and potentially dampen the response in flow. The Snake and Logan Rivers and Spring Valley are either in the Great Basin or on the eastern margin of the Rocky Mountains, suggesting there may be an east-west component to the regional hydroclimate. Previous work observed that the canonical ENSO dipole is modulated by changes in PDO [*Brown and Comrie*, 2004; *Wise*, 2010a] and shifts spatially through time [*Wise*, 2010a]. A denser network of tree-ring chronologies would improve the ability to characterize the modulation of climatic teleconnections, such as ENSO and PDO, on regional precipitation.

5.3. Implications for Water Management

[24] Our reconstructions of the Logan River suggest that overall flows were more variable at times preceding the instrumental period. Given that the reconstructions did not fully capture the magnitude of extreme events in the calibration period, it is likely that past droughts and wet periods are more extreme than the models indicate, thereby implying the possibility that water supplies may have been more volatile in the past. Not surprisingly, the reconstructions also suggest periods of greater flow variability than what is captured in the relatively short instrumental record, suggesting that water management decisions are based on a limited frame of reference when compared with the more

extensive reconstruction. That the instrumental record does not capture the full range of natural variability has been observed in studies in surrounding basins and across the western US [e.g., *Graumlich et al*., 2003; *Woodhouse et al*., 2006; *Timilsena et al*., 2007; *Watson et al*., 2009; *Barnett et al*., 2010; *Wise*, 2010b]. The potential for volatility in water resources may be compounded by the growing population in northern Utah which is expected to double by the year 2050, exceeding current supplies [*Utah Division of Water Resources*, 2000; *Mackun and Wilson*, 2011]. Reconstructions, such as those presented here, provide insights to water variability and availability, which would be of high value to water managers and regional planners.

6. Conclusions

[25] Logan River MAFs were extended back to 1605 using a suite of tree-ring chronologies, including seldom-used Rocky Mountain juniper. The higher sensitivity of the Rocky Mountain juniper chronologies relative to the more traditionally used Douglas-fir and limber pine suggests that Rocky Mountain juniper may be useful for future climate reconstructions [*Sieg et al*., 1996], particularly in areas where other species exhibit lower sensitivity. Additional work characterizing the climatic response of this species would help further determine its potential for dendroclimatology. This reconstruction was conducted in an area with complex and poorly understood climate teleconnections, due to its location in the transition zone of the western precipitation dipole, which is a product of interannual to interdecadal Pacific Ocean variability (i.e., ENSO, PDO) [*Mock*, 1996; *Wang et al*., 2009; *Wise*, 2010a]. The best Logan River MAF reconstruction model utilized tree-ring chronologies from the northern and southern portions of this transition zone, taking advantage of contributions from regions influenced by different aspects of the western precipitation dipole transition zone. As more tree-ring chronologies are developed, future work could better characterize the nature of this transition zone.

[26] Both reconstructions indicated the Logan River has experienced highly variable streamflow over the last four centuries that is only partly apparent when considering only the instrumental record. Current water supplies in northern Utah are able to meet demand, but even with per capita decreases in usage, demand is expected to outpace supply within the next decade due to increased population [*Utah Division of Water Resources*, 2000; *Mackun and Wilson*, 2011]. Persistent streamflow variability, coupled with the more recent shift in precipitation from snow to rain [*Gillies et al*., 2012], suggests the need for careful management of water resources. Water managers could benefit by utilizing an increasing array of information related to natural flow variability, such as the reconstructions presented herein, when allocating water resources.

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